UV

- The youngest stellar populations emit the bulk of their energy in the rest frame UV (<0.3μ); in the absence of dust attenuation, this is the wavelength range 'par excellence' to investigate star formation in galaxies over timescales of ≈10–300Myr,
- both O and B stars are brighter in the UV than at longer wavelengths.
  - the lifetime of an O6 star is ~6Myr, and that of a B8 star is ~350Myr.

The luminosity ratio of a O6 to B8 star at 0.16 μ is ~90, but, weighting by a Saltpeter IMF SSP for every O6 star formed, 150 B8 stars are formed.

Thus, at age zero, the UV emission from the collective contribution of B8 stars is comparable to that of O6 stars. And since B8 stars live a lot longer they dominate the UV flux on longer timescales.

(Calzetti 2012)

see MBW ***10.3.8 Star-Formation Diagnostics***

Today

The Origin Of The Mass–metallicity Relation:

Insights From 53,000 Star-forming Galaxies In The SDSS

Christy A. Tremonti focus on sec 1,3,6 and 8 Laura L.

For Nov 20 Weizhe

Stellar feedback in galaxies and the origin of galaxy-scale winds

Hopkins, Philip F.; Quataert, Eliot; Murray, Norman
2012MNRAS.421.3522H

OR

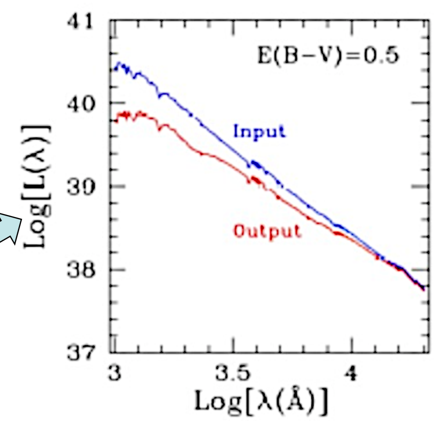
Optical-to-virial velocity ratios of local disk galaxies from combined kinematics and galaxy-galaxy lensing

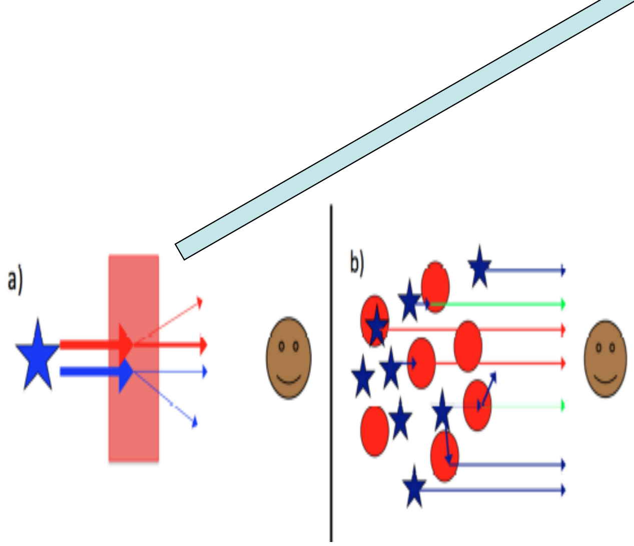
Reyes, R. et al sec 1,2,6 (sec 6.1,6.2)7,8 2012MNRAS.425.2610R

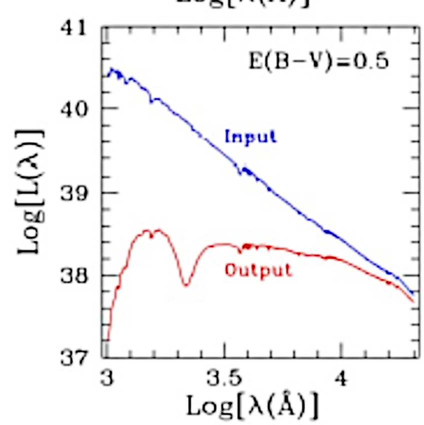
Star Formation Measures-UV Continuum

- in principle great- direct measure of total luminosity of young massive stars.
- Three big problems
  - DUST- UV extinction is much larger than in optical - light that is absorbed is re-emitted in the IR -the most active and luminous systems are also richer in dust, implying that they require more substantial corrections for the effects of dust attenuation; (MBW-10.3.8(b))
    - effects of dust are BIG- A_V =0.9 produces a factor ten reduction in the UV continuum at 1300Å (see MBW pg 479, S+G pg 33-34 for discussion of reddening- more later in lectures on dust)
  - Observations show that at 'low' SFR dust is not a big effect, at high values critical

Geometry is a serious issue- the same amount of dust has different effects depending on the relative position of the stars and the dust







UV Continuum

- at low redshift must observe from space – e.g. UV does not get thru the atmosphere
- VERY sensitive to IMF- at best can only constrain 15% of all the stars forming
- For a Kroupa IMF with with constant star formation

SFR(UV)$M_\odot$/yr = 3.0x10^{-47} L_{UV}(ergs/sec)(912-3000Å) (eq 10.108)- notice subtle difference due to different UV band assumed and Saltpeter IMF

IR Continuum

- Wavelength at which emission peaks is related to temperature of dust

8μ ~360k, 24μ ~121k, 70μ ~40k, 160μ ~20k based on Black Body Formula

λ_{peak}~29μ/T_{100} λ_{peak} in units of microns and T in units of 100k

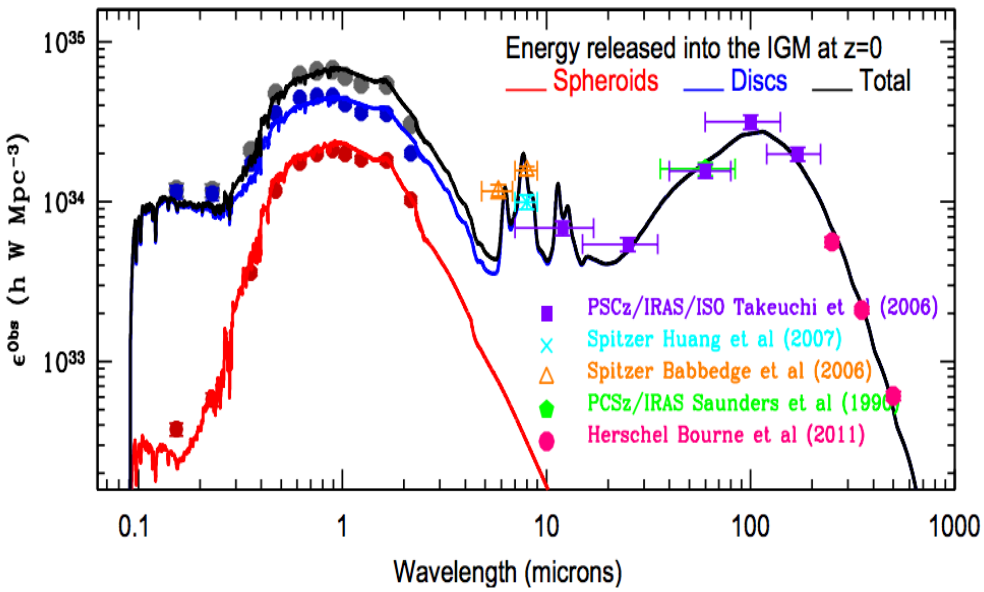
(these are the common wavelengths for IR space borne instruments IRAS, Spitzer, WISE, Herschel)

T~λ^{-1} but L~AT^4 so to get a lot of luminosity at long wavelengths needs a large emitting area, A

Temperature is set primarily by equilibrium; energy absorbed=energy emitted and physics of dust grains.

Energy Released By Galaxies

- Extensive galaxy surveys have allowed the measurement of the total energy released by all low z galaxies across the UV-far IR spectrum 1.3×10^{35} W/Mpc^3(Driver 20120; 35-45% of energy generated by stars is absorbed by dust and re-radiated in IR- this occurs predominately in spirals



IR Continuum

Most galaxies are dominated by T~20-40K dust, rapid star forming galaxies up to T ~100k.

Need wide range of temperatures to produce observed IR spectra.

Roughly SFR ($M_\odot$/yr)=$L_{total\ IR}$ $\times4.5\times10^{-44}$ ergs/sec (integrating IR from 8-1000μ)

Advantages- relatively free from extinction, **can do at high z with Herschel (remember the 'negative' K correction)**

Problems- requires lots of assumptions and scaling. Need to assume SF rate law (do problem 2.4 in S&G)

IR Continuum

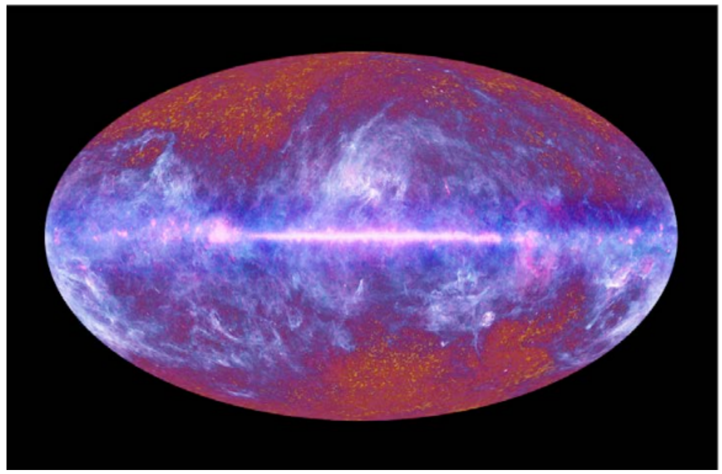
- Ideal for starburst galaxies because:
  - Young stars dominate UV-optical radiation, $\tau > 1$, $L_{IR} \sim L_{SB}$

and cross-section of the dust grains for stellar light is higher in the UV than in the optical

Not ideal for SF in disks of normal galaxies because:

a fair fraction of the IR luminosity is produced by dust re-radiation of emission from 'old' stars e.g. cirrus in the MW. -

the calibration between SFR and L_{IR} depends on the age of the system



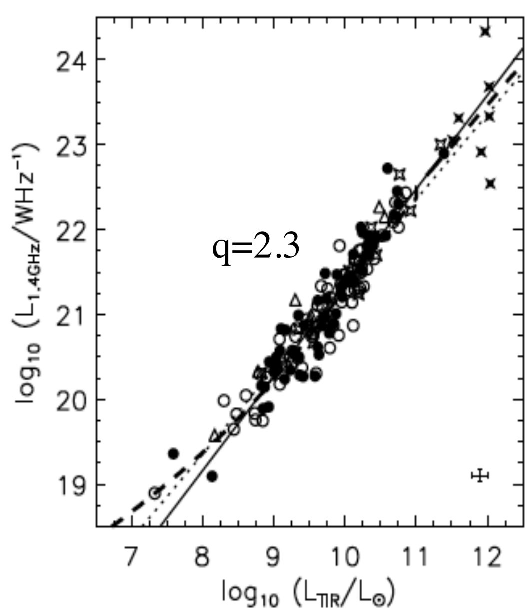
IR emission in Milky WAY

Star Formation- Radio View

$$q = log\left(\frac{FIR}{3.75 \times 10^{12} \mathrm{W\ m^{-2}}}\right) - log\left(\frac{S_{1.4GHz}}{\mathrm{W\ m^{-2}\ Hz^{-1}}}\right)$$

Radio continuum emission from star-forming galaxies has two components:

- thermal bremsstrahlung from ionized Hydrogen
- non-thermal synchrotron emission from cosmic ray electrons spiraling in the magnetic field of the galaxy
  - The relative ratio is frequency dependent because of the different spectral slopes of the 2 processes ($F_\nu \sim \nu^\alpha$, α=-0.7 for synch, -0.1 for TB)
- This method does not depend on how one handles dust or ionizing continuum,
- But physics is not fully understood- why cosmic rays/magnetic field are so finely tuned so that radio synchrotron traces star formation



Bell 2002

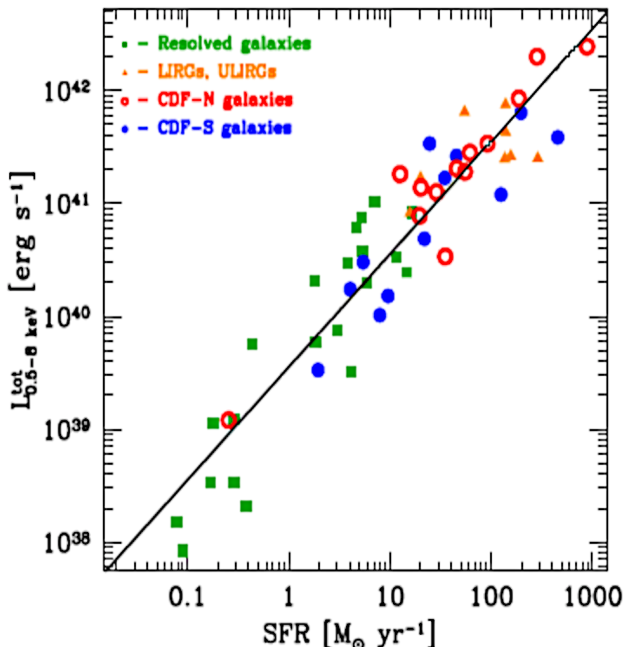
Star Formation X-rays

Mineo et al 2012

- In a rapidly star forming galaxies x-rays are primarily produced by
1) high mass x-ray binaries with a lifetime $\tau \sim 2\times10^7$yrs Hard x-rays
   surprisingly the luminosity function of these sources is very similar from galaxy to galaxy with only the normalization~SFR changing

2) hot gas from Supernova- soft x-rays results imply that only 5% of SN energy is needed to produce "diffuse" x-rays

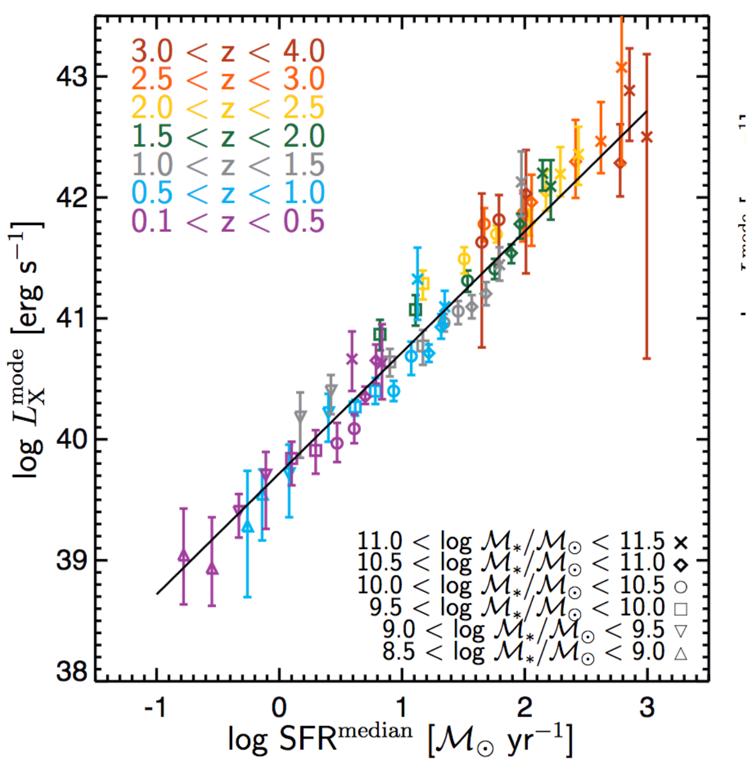
major advantage of x-rays: do not need to be concerned about dust, can do this at high redshift



X-ray luminosity vs SFR

X-ray Indicator of SF

- Aird et al 2017 shows that this relation between x-ray luminosity and SF 'works statistically ' (with a correction due to evolution) out to z~4 !



Review-How to Infer SFR from Optical Data

- Construct stellar evolutionary tracks containing parameters such as T_{eff}, L_{bol},
- These are typically obtained via atmospheric models & spectral libraries

Construct IMFs containing parameters such as Luminosity, Color, Spectra of Single Age Population

- Add together IMFs from step 2 to get spectra & colors of a galaxy with an arbitrary star formation history
- Lots of parameters to determine (see Papastergis et al 2013 http://arxiv.org/pdf/1208.5229.pdf) for a detailed discussion of the steps and uncertainties

1) Star Formation History

2) Galaxy Age

3) Metal Abundance

4) IMF

One iterates by comparing the actual galactic emission to the output of a set of galactic stellar population models. The models that best fit the observed data are then used to estimate the galactic properties of interest (e.g. stellar mass, present star formation rate, internal extinction etc.);

How to handle dust??

The Procedure

- a library of model SEDs are generated, using the Bruzual & Charlot (2003) stellar population synthesis code and assuming a Chabrier (2003) stellar initial mass function (IMF).
- Models with an extensive range of internal extinction, metallicity and star formation histories are considered.
  - In particular, star formation history templates include both an exponentially declining component as well as random starburst episodes.
- The stellar mass, star formation rate, internal extinction etc.) are computed as the average of all model values, where each model is weighted according to its fit likelihood.

"1σ" uncertainties of the physical properties are also be derived

The median 1σ uncertainty in $\log M_*$ is 0.086 dex, or about 22%

- It is important to note that stellar mass estimates of the same galaxy obtained with different methods can have systematic offsets of up to factors of a few.

- Papastergis et al 2013

Uncertainties in Estimating Stellar Masses

- Star formation history- only in a few nearby galaxies can the star formation history be directly determined from H-R diagrams
  - e.g. LMC an initial burst of star formation(1/2 mass formed), then a quiescent epoch from ~12 to 5 Gyr ago. Star formation then resumed and continues at an average rate of roughly 0.2 $M_\odot$/yr, with variations at the factor-of-two level (Harris and Zaritsky 2010)
- IMF uncertainty: fundamental, factor of 2 in transformation of light to mass (also how many binaries!)
- Metalliticity: less important (30% effect)
- Different stellar evolution codes- can be very important at different ages (factor of 2)
- Spatial variation in SF history/rate

SF Histories

- see Tosi 0901.1090.pdf for a review-Its very hard to do beyond the local group

Star Formation Histories 7

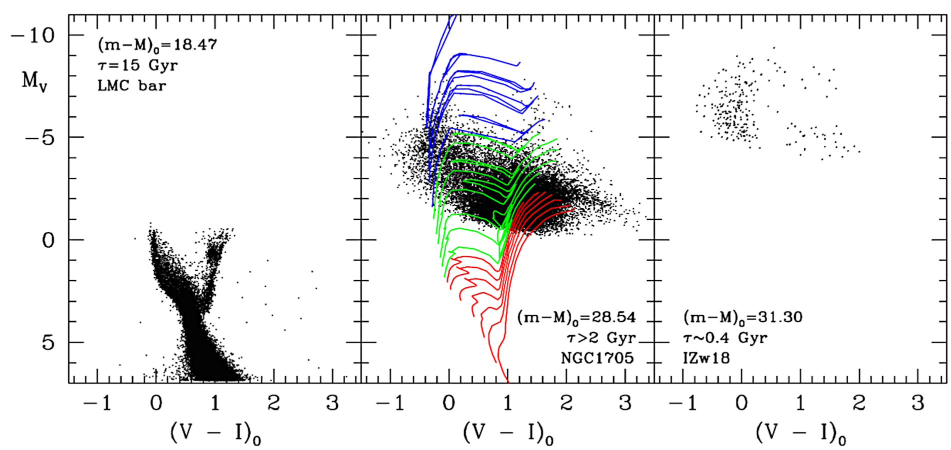


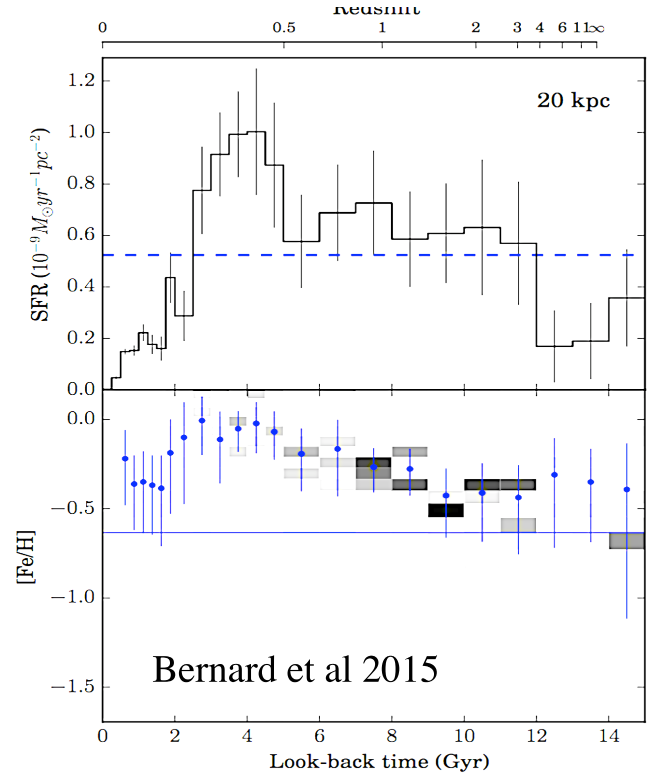
Figure 5. Effect of distance on the resolution of individual stars and on the corresponding lookback time τ for the SFH. CMD in absolute magnitude and colour of systems observed with the HST/WFPC2 and analysed with the same techniques, but at different distances; from left to right: 50 Kpc (LMC bar), 5.1 Mpc (NGC1705) and 18 Mpc (IZw18). The central panel also shows stellar evolution tracks from Fagotto et al. (1994b) for reference: red lines refer to low-mass stars, green lines to intermediate mass stars, and blue lines to massive stars.

SF History of a Spiral

- M31 has some of the best data
- In general
  - The disc formed most of its mass (~65 percent) since z~1 (8 Gyr ago)

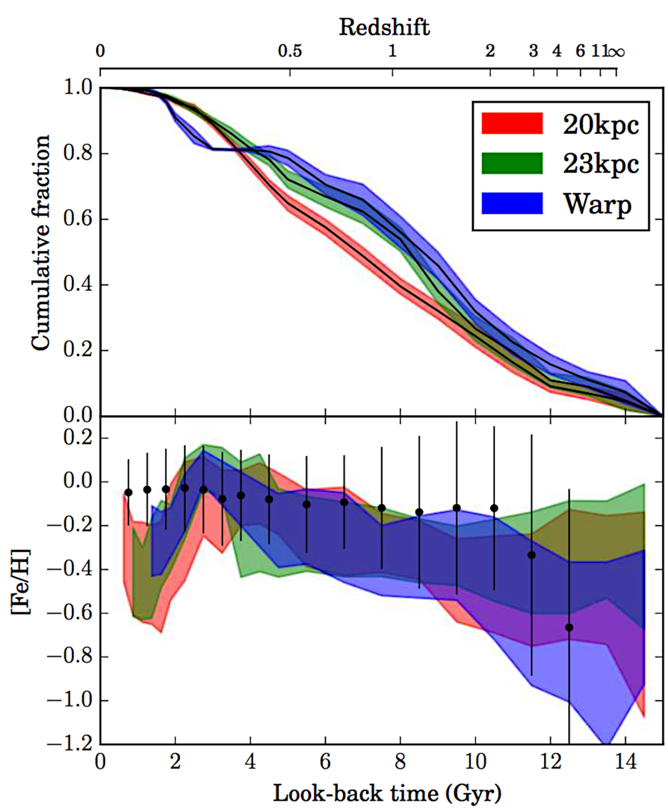
giving a median age of 7 Gyr,

  - with one quarter of the stellar mass formed since 5 Gyr .



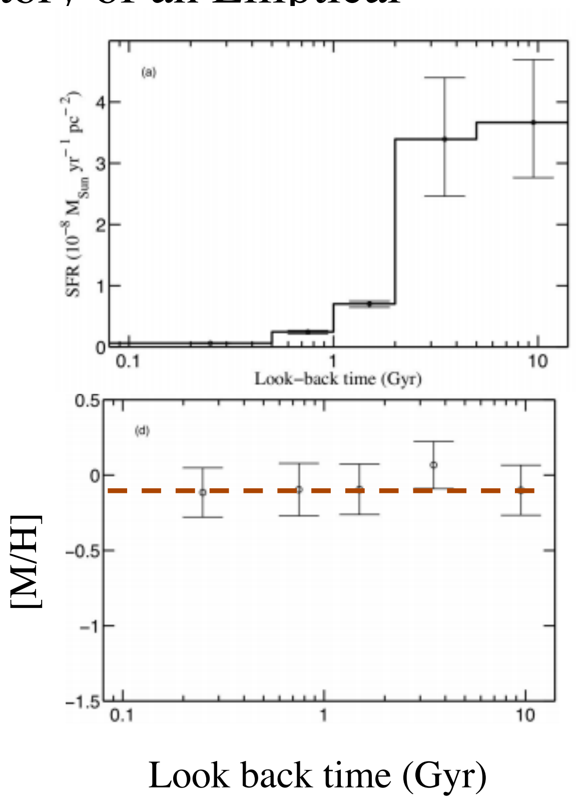
SF History of M31

- Bernard et al 2015



Star Formation History of an Elliptical

- M32- a dwarf elliptical companion of M31 (close enough to have a CMD for resolved stars)-
  - **very different history than the LMC or M31**
- ~95% of its mass formed 5-14 Gyr ago. 2 dominant populations; ~30% ± 7.5% of its mass 5-8 Gyr old population, ~65% ± 9% of the mass in a 8-14 Gyr old population (Monachisi et al 2012)
- **Metallicity does not change with time** (!)- where do the created metals go (another lecture)

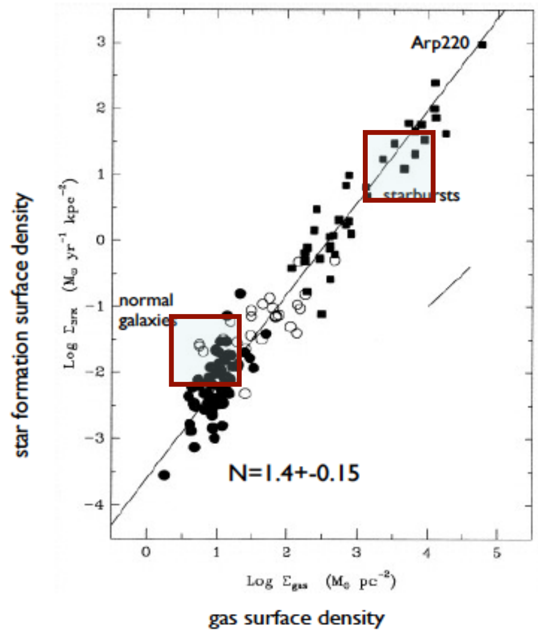


Observation of NGC5128

- The nearest giant elliptical Rejkuba et al 2017 (2 colors 12 orbits each)
- 2-burst simulations 'work' to produce observed CMD and luminosity functions a component of age ~12Gyr (80% of mass) and a younger component of 2-6 Gyr
- Both are alpha enhanced.

Kennicutt Schmidt Law (MBW sec 9.5)

- Assume that SFR rate is proportional to total amount of gas
- SFR~ρ_{gas}~$d\rho_{gas}/dt$; sol't ρ_{gas} ~$\rho(0)_{gas}e^{-t/\tau}$
- More generally assume SFR~ρ^{n}_{gas}-
  - e.g. as gas compresses stars form more easily or there maybe another timescale in the process such as the free-fall time of the gas
- **Frequently this expressed in terms of surface density Σ_{SFR} (an observable)**



Kennicutt 1998

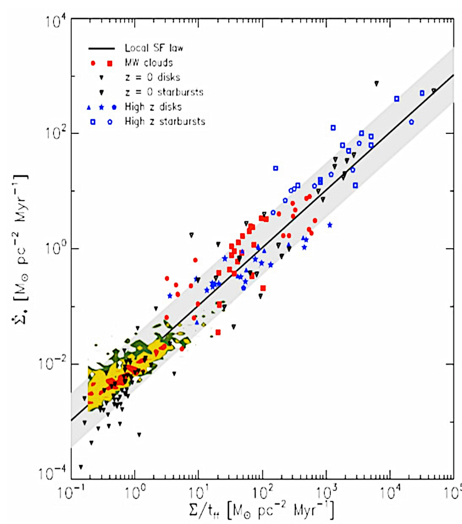
- The motivation for this scaling comes from the gravitational instability of cold gas-rich disks, although the normalization depends on feedback physics.

- $\Sigma_{SFR}=A\Sigma^{n}_{gas}$ n~1.4 can be explained by.....

  stars form with a characteristic timescale equal to the free–fall time in the gas disk, which in turn depends inversely on the square root of the gas volume density, τ_{ff} ~$\rho^{-1/2}_{gas}$ **for a fixed scale height ρ_{gas}~**Σ_{gas} (MWB eq 9.22)

gas consumption efficiency is low; takes ~1.5x10^{9}yrs to convert the gas into stars

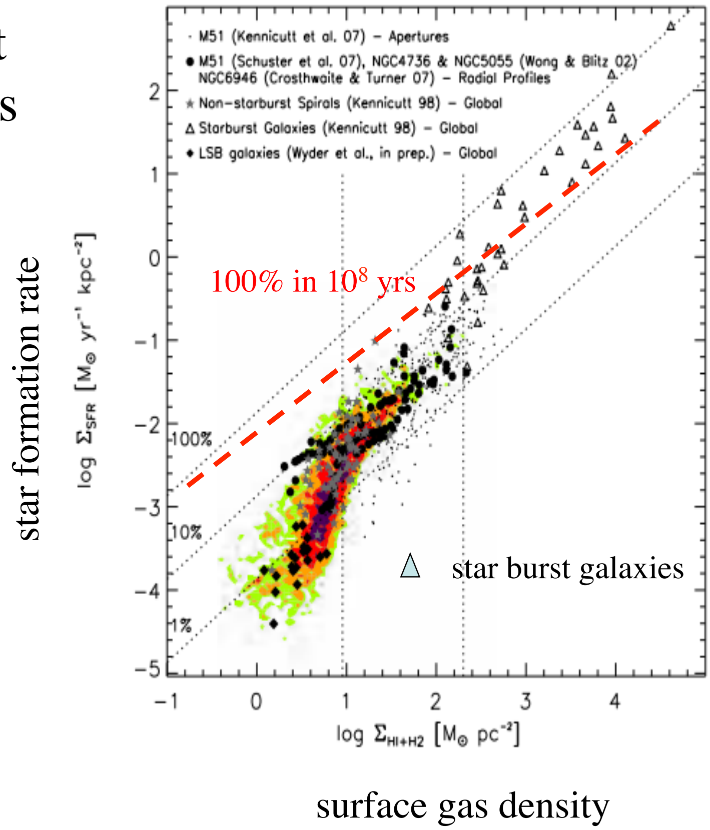
Kennicutt Schmidt Law (MBW sec 9.5.1)



Not only for whole galaxies but also for parts of them (Krumholz et al. 2012).

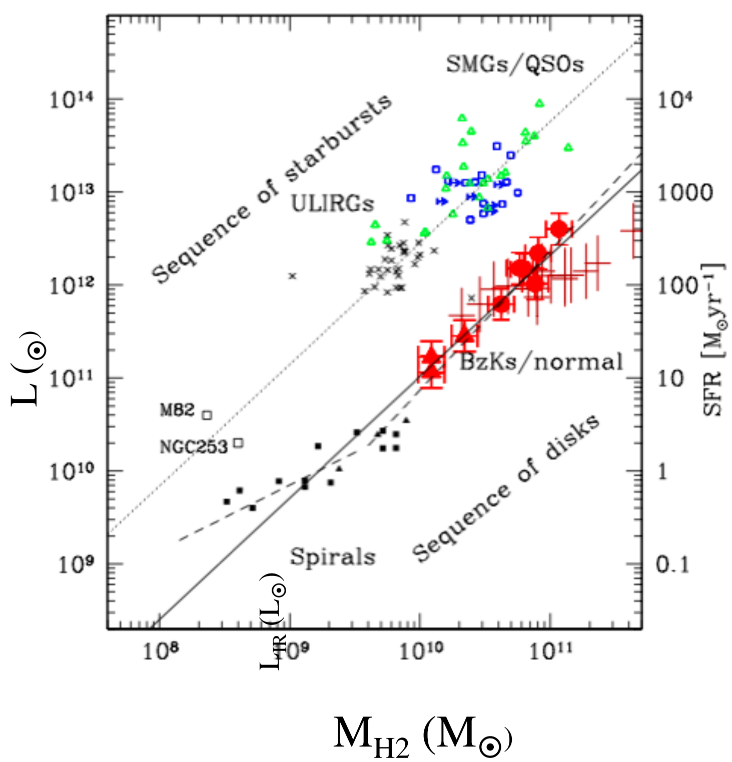
Kennicutt-Schmidt Law with Starbursts

- starburst galaxies- the highest star forming rate galaxies obey a different law
- They seem to convert the gas into stars 'as fast as possible'-e.g on freefall timescale.
- This produces a wind as a large amount of energy is injected by star formation in a short time.



Star Bursts

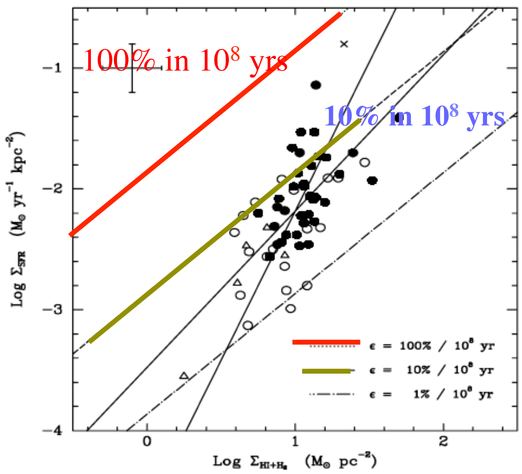
- In the low redshift universe there are very few, very high SFR objects- these are much more important in the high z universe
- It appears that the relations for very rapid SF galaxies are different



- SF in normal galaxies uses about 5% of available gas every 10^8 yrs !
  – But this does not include 'recycling'- e.g. when stars die they recycle gas back into the ISM
- Since the typical gas mass fraction in disks ~ 10-20% of baryonic mass (but changes a lot as a function of mass), implies that stellar mass of the disk grows by about 1% per 10^8 years, i.e. the time scale for building the disk (at the present rate) is ~ Hubble time.
- In terms of the average gas depletion timescale, ~ is 2.1 Gyr.
- *Recycling of interstellar gas from stars extends the actual time scale for gas depletion by factors of 2–3*

How Long Does the Gas Last

surface mass density of star formation



surface mass density of gas (HI+H_2)

Relationship for 'normal' star formation
Kennicutt 1998

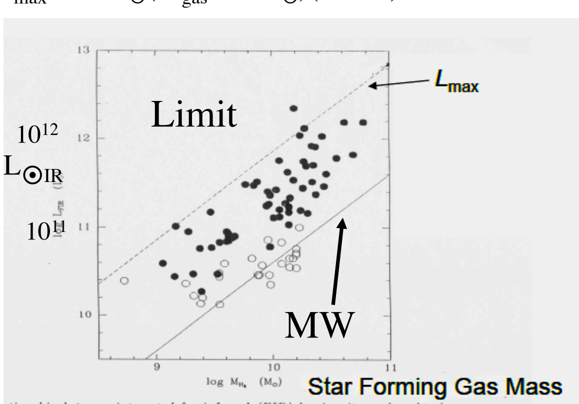
- Starburst use up their gas much faster
  – <30%> of gas used every 10^8 yr
  – Depletion timescale≈ 0.3 Gyr
- How luminous are these objects?

SFR_{max}~100M/yr(Mgas/$10^{10}M_\odot$)(10^8yrs/Δt_{dyn})

Now nuclear fusion is ~0.7% efficient the fraction of rest mass convert to energy for a Saltpeter IMF is ε~0.05 during 10^8yrs

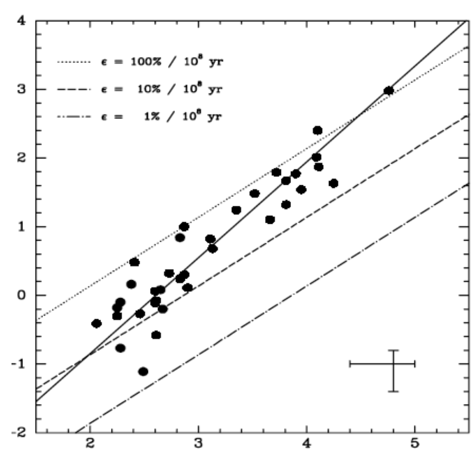
This gives L_{max}~0.07ε(dM/dt)c^2

L_{max}~$10^{11}L_\odot(M_{gas}/10^{10}M_\odot)(\varepsilon/0.05)$



How Long Does the Gas Last- Star Bursts

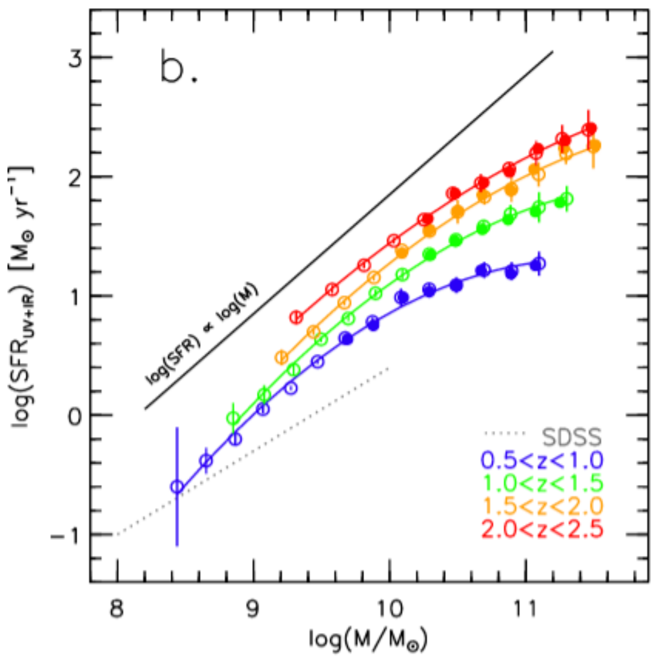
log Σ_{SFR} ($M/_\odot$yr-kpc^2)



log Σ_{H1+H2} ($M_\odot$/pc^2)

'Main Sequence' of Star Formation

- Galaxy surveys out to z~3 show that the majority of star-forming galaxies follow a relatively tight relation between star formation rate (SFR$\equiv\Psi$) and stellar mass ($M_\star$) varying with redshift (Brinchmann et al. 2004;Noeske et al. 2007; Elbaz et al. 2007)
  - **this is called the main sequence of star formation**



Whitaker et al 2015

Low Z SFR-Summary

Kennicutt 1998

Property	Spiral Disks	Star Bursts
Radius	1 – 30 kpc	0.2 – 2 kpc
SFR	0 – 20 $M_\odot$ yr^{-1}	0 – 1000 $M_\odot$ yr^{-1}
Bolometric Luminosity	10^6 – 10^{11} $L_\odot$	~~10^6 – 10^{13}~~ $L_\odot$
Gas Mass	10^8 – 10^{11} $M_\odot$	10^6 – 10^{11} $M_\odot$
Star Formation Timescale	1 – 50 Gyr	0.1 – 1 Gyr
Gas Density	1 – 100 $M_\odot$ pc^{-2}	10^2 – 10^5 $M_\odot$ pc^{-2}
Optical Depth (0.5 μm)	0 – 2	~~1 – 1000~~
SFR Density	0 – 0.1 $M_\odot$ yr^{-1} kpc^{-2}	1 – 1000 $M_\odot$ yr^{-1} kpc^{-2}
Dominant Mode	steady state	steady state + burst

- $t_{freefall}=(R/G\Sigma)^{1/2}$
- $t_{cross}=(R/\sigma)$
- the fastest things can happen is when this are equal and make R the Jeans length

  $R_{Jeans}\sim\sigma^2/G\Sigma$

Basic Equations of Star Formation- see S+G 4.3.2

(1) $M = M_s + M_g$

$\begin{cases} M = \text{total mass in baryons} \\ M_s = \text{mass in stars} \\ M_g = \text{mass in gas} \end{cases}$

(2) $\frac{dM}{dt} = f - e$

$\begin{cases} f = \text{rate of infalling gas} \\ e = \text{rate of ejected gas} \end{cases}$

(3) $\frac{dM_s}{dt} = \Psi - E$

$\begin{cases} \Psi = \text{star formation rate} \\ E = \text{gas ejection rate of all stars} \end{cases}$

(4) $\frac{dM_g}{dt} = -\Psi + E + f - e$

- D. Elbaz; based on Tinsley 1980, Tinsley 1980, Fund. Of Cosmic Physics, 5, 287-388; Maeder 1982

Reminder-Jeans Criterion for collapse of spherical cloud MBW pg 167, sec 8.2.3, 9.1.2

- Gravitational instability sets in if the free-fall time is less than the sound crossing time
- $t^2_{ff}=1/G\rho<(R/c_s)^2=10^8 n^{-1/2}_H$ yrs;
- free fall time from $d^2r/dt^2=-GM/r^2$; n_H is the number density of gas
- hydrodynamical timescale from $d^2r/dt^2=(-1/\rho(r))dP/dr= R/c_s$

Characteristic mass for system to collapse is Jeans Mass

Reminder-Jeans Criterion for collapse of spherical cloud

Jeans mass $M_J = 4/3\pi\lambda^3{}_J\rho = 4/3\pi c^3{}_s\rho^{-1/2}$

Jeans length $\lambda_J = \mathrm{sqrt}(\pi c_s{}^2/G\rho)$– distance a sound wave travels in a grav free-fall time

For typical values

- $M_J = [\pi^{5/2}/6][c^3{}_s/(G3\varrho)^{1/2}] \sim 40M_\odot[\,c_s/0.2\mathrm{kms}^{-1}]^3\ \ n_{H2}/100\mathrm{cm}^{-3}]^{-1/2}$

$M_{J\ \mathrm{SOLAR\ UNITS}} = (T/10k)^{3/2}(n_H/10^5\mathrm{cm}^{-3})^{-1/2}$

units of surface mass density $\lambda_J = c_s{}^2/G\Sigma$

c_s= sound speed=sqrt(dP/dρ)=sqrt($k_B T/\mu m_H$) for hydrogen (k_B= Boltzmann's constant, m_H= mass of hydrogen atom, μ = mean molecular weight)

- For typical values c_s=0.3km/sec$(T/10k)^{1/2}$

However the gas cannot collapse unless it can radiate away the heat from conversion of potential energy so need $t_{cool} < t_{ff}$ the rate at which gas cools depends on a strong function of temperature and the density squared.

if one has an external pressure MBW eq 9.3

- For an isothermal sphere in pressure equilibrium with its surrounding,
- $M_{BE} = 1.182c^3{}_s/(G^3\varrho)^{1/2} = 1.182c^4{}_s/(G^3P_{th})^{1/2}$
- where $P_{th} = \rho c^2{}_s$ is the surface pressure
- M_{BE} the largest mass that an isothermal gas sphere embedded in a pressurized medium can have while still remaining in hydrostatic equilibrium. Clouds of gas with masses greater than the Bonnor–Ebert mass must inevitably undergo gravitational collapse to form much smaller and denser objects.

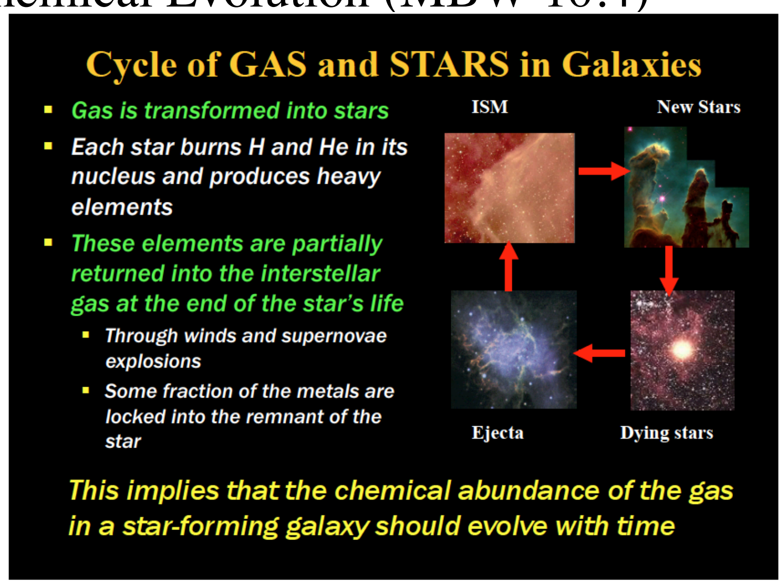
Gravitational Instability

- Another derivation of Jeans length/mass
- Balance pressure and gravity (pg 355 of S+G)
- Potential energy= $-1/2 \int \rho(x)\phi(x)d^3x \sim G\rho^2 r^5$
- if gas moves as sound speed $KE=c_s^2 M$
  - $M=4/3\pi\rho r^3$

- In equilibrium viral theorm says KE=PE/2 so define a length λ_j where that is true and get $\lambda_j=c_s \mathrm{sqrt}(\pi/G\rho)$

The cloud's radius is the Jeans' Length, $\lambda_{j,}$ and its mass $(4/3\pi\rho\lambda^3_j)$ is the Jeans mass -when thermal energy per particle equals gravitational work per particle. At this critical length the cloud neither expands nor contracts. Dimensionally this is $kT=GM/r$

Basics of Chemical Evolution (MBW 10.4)



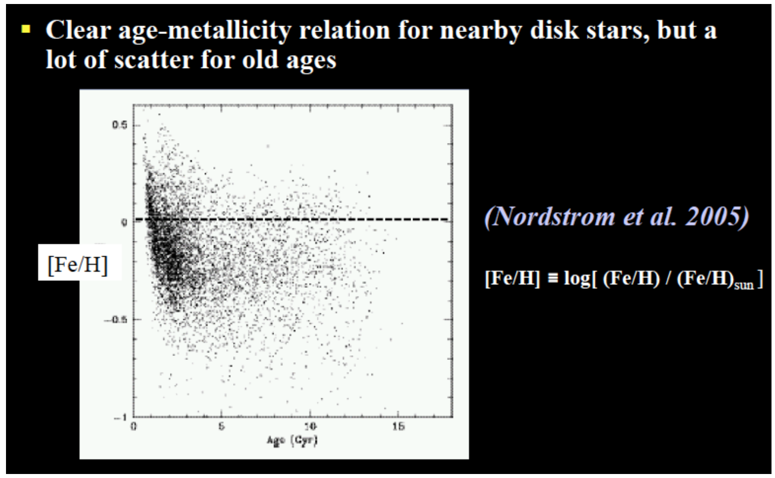
- H and He were present very early on in the Universe, while all metals (except for a very small fraction of Li) were produced through nucleosynthesis in stars
- The fraction **by mass** of heavy elements is denoted by Z

–

The Sun's metal abundance $Z_{sun} \sim 0.02$

– The most metal-poor stars in the Milky Way have $Z \sim 10^{-5}$ -- $10^{-4}\ Z_{sun}$

Generic Predictions



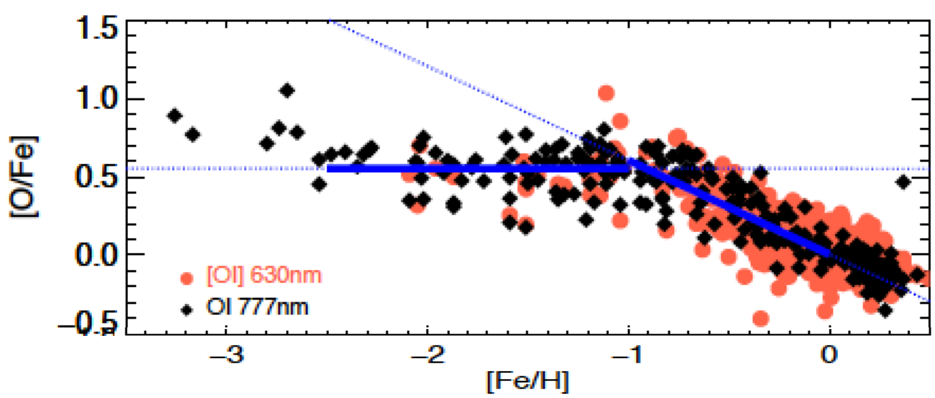
- If a galaxy is a **closed box** predict increase of metallicity with time
- Since alpha elements are mostly produced by SnII (from massive short lived stars) while significant amounts of Fe from type Is (longer lived white dwarf binaries) change in chemical composition with age

Pagels Nucleosynthesis and chemical evolution of galaxies1997 - intro at http://ned.ipac.caltech.edu/level5/Pagel/frames.html
Review article
1997ARA&A..35..503
Andrew McWilliam,
Abundance Ratios and Galactic Chemical Evolution

Chemical Composition vs Stellar Age

- At low Fe abundance high O/Fe- predominance of short timescale (type II) SN in early universe over long time scale (Type I) SN at early times

Amarsi, M. Asplund, R. Collet, and J. Leenaarts 2015



Summary

- The star formation rates is determined using many different indicators.
- The most important of are
  - far infrared emission tracing deeply embedded star formation
  - Hα emission tracing H II regions;
  - and far ultraviolet emission tracing young, massive stars that have dispersed their natal gas and dust.
  - Radio emission tracing relativisitic particles created by SF processes (e.g. supernova)
- Molecular hydrogen surface density correlates linearly with star formation rate -HI seems not to matter-